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Using Three Dimensional Structural Simulations to Study the Interactions of Multiple Excavations in Salt

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ABSTRACT

Three-dimensional quasistatic finite element codes are being used at Sandia National Laboratories to simulate the interactions of multiple large room and pillar mines in rock salt. The calculations presented in this paper are of a salt dome which contains multiple closely-spaced room and pillar mines. One of the mines was used as an oil storage facility, supported by the US DOE under the auspices of the Strategic Petroleum Reserve (SPR) program. The facility has recently been decommissioned due to the discovery of geotechnical instabilities. The model, validated by field observations, has resulted in a better understanding of the mechanisms which can threaten the stability of an underground excavation, as well as the structural interactions of multiple excavations. Although these calculations were performed in the specific interest of the SPR, the results should be of interest to mine designers concerned with the interactions of multiple mines excavated in a common formation.

KEYWORDS

Salt, Storage, Simulation, Computational Mechanics, Finite Element, Creep

INTRODUCTION

The US Strategic Petroleum Reserve (SPR) is an oil storage facility created by the United States Department of Energy (DOE) to reduce the vulnerability of the nation to interruptions in foreign oil supply. The SPR currently stores approximately 560 million barrels (MMB) of crude oil in underground caverns in salt domes at four sites located along the Gulf of Mexico. Until recently, 70 MMB of that oil was stored in an abandoned room and pillar mine located at Weeks Island, Louisiana. A plan view of the Weeks Island salt dome is shown in Figure 1. The SPR oil storage facility is a two-level room and pillar mine which was acquired from Morton Salt Company. The upper level (163 m) was mined from 1902 to 1955. Mining of the lower level (224 m) began in 1955 and continued until the DOE purchased the mine in 1976. The 1976 purchase agreement allowed Morton to continue utilizing the existing mine shafts for development of an interim mine, known as the Markel Mine, while two shafts were being sunk for the New Morton Mine. The Markel Mine was mined at the same depth as the upper level of the SPR facility and was active until 1981 when the New Morton mine shafts were completed and the SPR facility was filled with oil. The New Morton Mine is an active salt production mine to the present day.

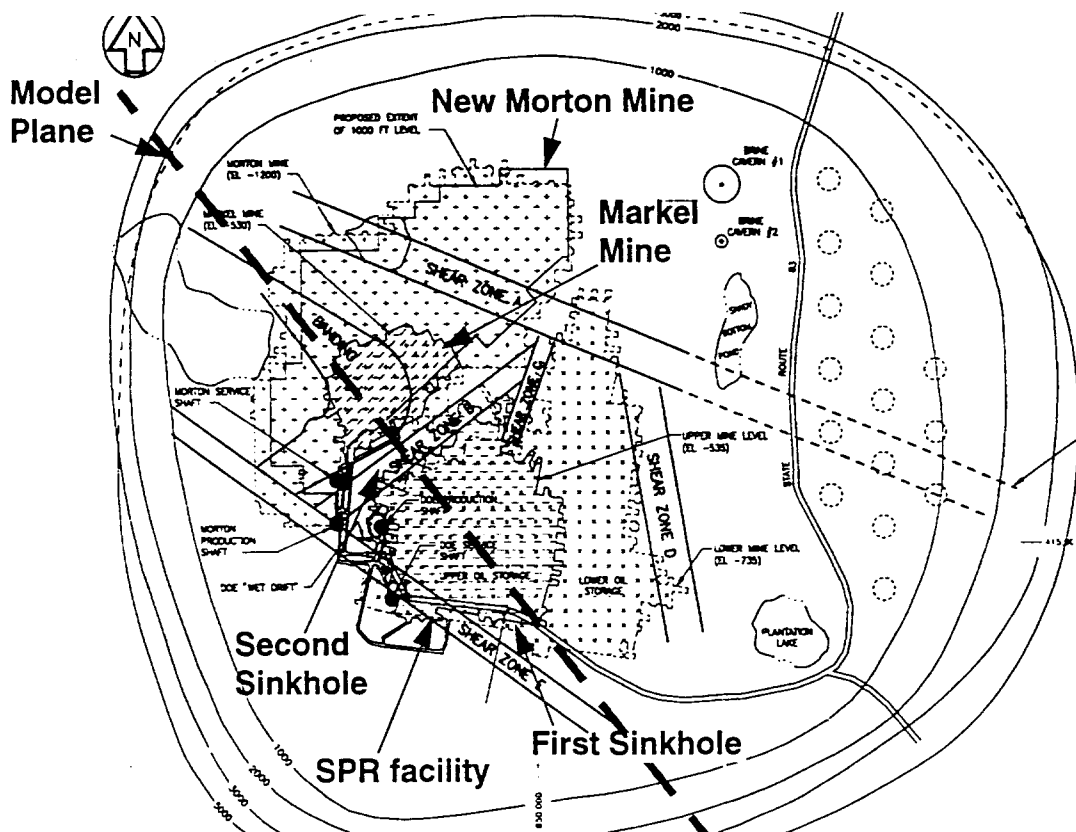


Figure 1: Locations of mines at Weeks Island, including the SPR oil storage facility, the Markel Mine, and the New Morton Mine.

In December 1994 the DOE announced that it would decommission the Weeks Island SPR facility because of apparent geological instabilities that posed a significant threat to the oil stores and the environment. Closure of the facility was motivated by the discovery of a sinkhole (shown in Figure 1) over the southern edge of the facility in May 1992 (Bauer *et al.*, 1996). A second sinkhole was discovered over the northwest edge of the mine in February 1995. Three dimensional finite element simulations of the facility (Hoffman and Ehgartner, 1996) predicted areas near the mine perimeter to be in tension. Furthermore, a dilatant zone was predicted, using a criterion developed specifically for Weeks Island salt (Ehgartner, 1994), extending from the top of the salt dome down to the edge of the mine. Dilatancy is characterized by increased porosity, hence permeability, caused by microfracturing. The tensile stresses and dilatant damage were predicted to be greatest over the mine edges where the upper and lower levels are vertically aligned. With both sinkholes forming over vertically-aligned boundaries, these calculations suggest a credible explanation that groundwater inflows in dilatant zones around the mine perimeter may have resulted in their formation. An influx of water into the mine could force the stored oil out of the mine, posing a serious threat to the oil stores and the environment.

With the decision to decommission the Weeks Island SPR facility made, the DOE was interested in investigating various long term options for abandonment which would minimize the impact on the neighboring Morton salt production mine. The decommissioning plans called for the relocation of the oil reserves to other SPR facilities followed by brine filling of the Weeks Island SPR facility. Before brine filling, the DOE wanted to be sure that the SPR facility was not hydrologically coupled to either the Morton or Markel facilities. Although all three of the Weeks Island facilities have been individually studied, the coupled effects of the facilities had never been studied as the inclusion of all three facilities in a single model was considered too computationally demanding. Hence, not much is known about the interactions of closely-spaced mines. This paper presents three dimensional (3D) finite element simulations of the Weeks Island salt dome (including all three mines) which were performed to evaluate the effect of closing the SPR facility on the Morton mine. The simulations utilize a 3D planar representation of the salt dome and excavated facilities, representing a compromise between a plane-strain representation of the facility and a full 3D simulation. The simulations investigate the effects of various decommissioning scenarios. Although this work was performed to address issues of specific interest to the DOE, these calculations have identified performance issues regarding multiple excavations in salt which should be of interest to mine operators.

Sandia has a long history of research and development in nonlinear large strain finite element codes and the application of these codes to geomechanics problems in waste management programs. Sandia's quasistatic finite element technology is based on iterative solvers and has been extensively developed for large problems involving geometric and material nonlinearities. The use of iterative solvers and experience with nonlinear material response provides a base technology that offers efficient solution of very large complex geomechanics problems. The finite element code used in the present calculations, JAC3D (Biffle, 1993), uses an eight-node hexahedral Lagrangian uniform strain element with hourglass stiffness to control zero energy modes. A nonlinear conjugate gradient method is used to solve the nonlinear system of equations. This efficient solution scheme is much faster than the direct solvers which are used in most commercial codes.

Geometric Model

As can be seen in Figure 1, the Weeks Island facilities are complex and highly irregular. The computational requirements of performing such a simulation would likely exceed the capabilities of most computing environments. As a practical compromise, the present simulations utilize a three dimensional planar representation of the Weeks Island dome (shown in Figure 2) which has a unit thickness, where one unit includes half a room and half a pillar. Both sides of the unit cell are assumed to be symmetry planes. The planar model is based on a NW diagonal slice across the dome, as shown in Figure 1. This approach represents a compromise between a plane-strain representation of the facility and a full three-dimensional simulation. Like a plane strain representation, the model has an infinite out-of-plane depth. Because it is a 3D simulation, more accurate modeling of pillar deformations can be accomplished than with a plane strain model. The model includes relevant parameters of the three mines such as depth, width and extraction ratio. The problem with developing a model of unit thickness is that the three facilities have slightly different room and pillar dimensions. The actual dimensions and extraction ratios are given in Table 1 for all three facilities. The room and pillar dimensions of the SPR and New Morton mines were averaged to obtain the out-of-plane

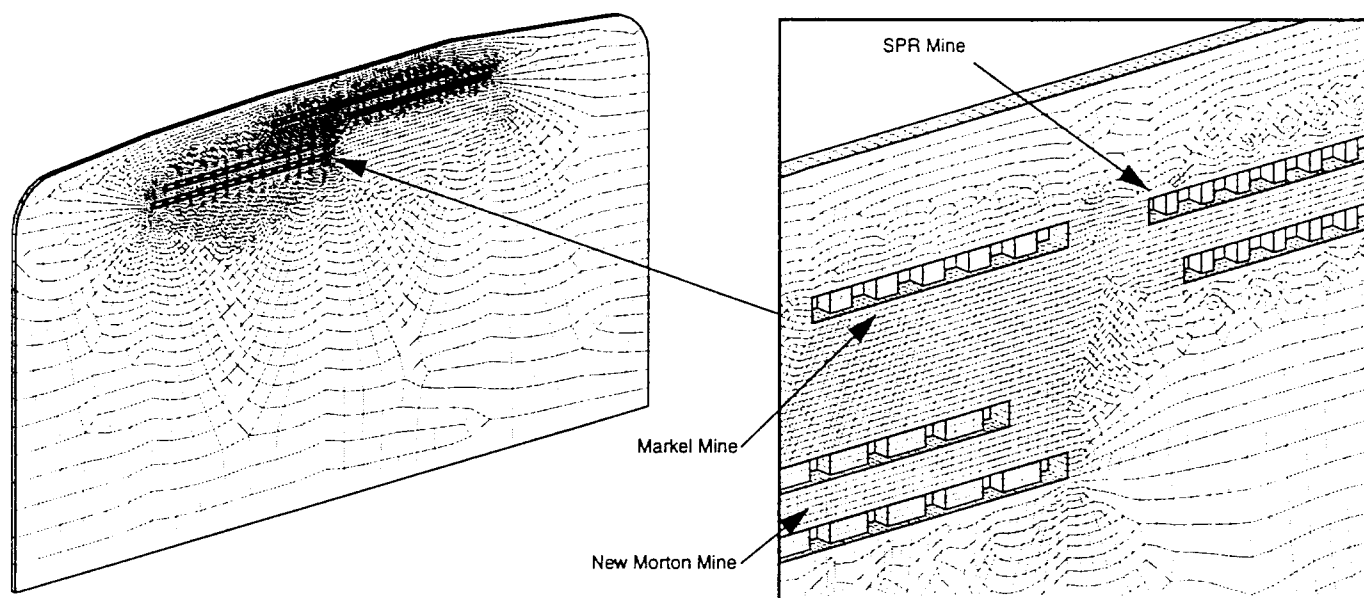


Figure 2: Finite element representation of the Weeks Island dome, including the SPR, Morton, and Markel facilities. The model contains 55,630 nodes and 41,584 elements.

TABLE 1
ROOM AND PILLAR DIMENSIONS FOR ACTUAL MINES AND THOSE USED IN THE MODEL

Mine	Actual Dimensions			Calculated Dimensions for Infinite Array Model			
	Pillar Width (m)	Room Width (m)	Extraction Ratio	Avg Pillar Depth (m)	Avg Room Depth (m)	Pillar Width (m)	Room Width (m)
SPR	30.5	15.2	.55	34.3	17.5	27.1	13.3
Markel	29.0	22.9	.69	34.3	17.5	24.4	27.7
Morton	38.1	19.8	.57	34.3	17.5	42.3	22.8

pillar and room depths. The in-plane room and pillar widths were calculated to maintain the extraction ratios. The calculated model dimensions are also given in Table 1. All of the rooms in the model are 22.86 m-high.

Boundary and Initial Conditions

Symmetry boundary conditions are applied to the two vertical planes of the model. Vertical displacements are constrained along the lower horizontal boundary of the model. Gravitational body forces are applied to the model. To ensure initial equilibrium, elevation-dependent initial stresses are applied to each element in the model based on the following equation:

$$\sigma_{init} = \rho_{ob} g d_{ob} + \rho_s g (d - d_{ob}) \quad (1)$$

where ρ_{ob} and ρ_s are the density of the overburden (1874 kg/m^3) and salt (2300 kg/m^3); d is the depth of the element centroid; d_{ob} is the thickness of the overburden (38.1 m); and g is the gravitational constant. The first term of this equation is a constant, accounting for the overburden layer which is not explicitly modeled. The second term is the gradient of the depth dependent initial stresses and increases proportionally to the density of salt. An initial stress state is assumed in which the horizontal stress components are equal to the vertical stress component (lithostatic). To simulate the rock mass surrounding the salt dome, a depth dependent traction boundary condition consistent with Equation (1) was applied to the surface of the dome.

The finite element model includes a depth-dependent temperature gradient which starts at 26.8°C at the surface and increases at the rate of 0.0222°C/m . The temperature distribution is important because the creep response of the salt is temperature dependent.

Mining History

The present calculations simulate the history of the Weeks Island mining operations as summarized in Table 2. The time-dependent, sequential excavation of the three Weeks Island facilities was simulated through the use of pressure boundary conditions applied to the mine walls which were linearly reduced from lithostatic to zero pressure over a specified period of time. As shown in Figure 3, each level of the SPR and Morton facilities was divided into several equally sized regions so that the sequential excavation of the mine could be simulated. The actual excavation time was divided by the number of regions to determine the period over which the applied pressure should be reduced to zero. Each region was then sequentially reduced to zero, simulating the excavation process. The initiation of the simulations ($t = 0$) corresponds to the year 1902.

TABLE 2

MINE HISTORY AND SEQUENCE OF TRACTION BOUNDARY CONDITIONS USED TO SIMULATE EXCAVATION

Mine	Simulated Mine Dates	Region	Pressure Ramp	
			start time (yrs) $P = \text{lithostatic}$	finish time (yrs) $P=0.0$
SPR upper level	1902-1955	upper level, 1	0.0	17.6
		upper level, 2	17.6	35.3
		upper level, 3	35.3	53.0
SPR lower level	1955-1976	lower level, 1	53.0	58.25
		lower level, 2	58.25	63.5
		lower level, 3	63.5	68.75
		lower level, 4	68.75	74.0
Markel	1977-1980	entire mine	75.0	78.0
New Morton Mine lower level	1980-1988	lower level, 1	78.0	80.0
		lower level, 2	80.0	82.0
		lower level, 3	82.0	84.0
		lower level, 4	84.0	86.0
New Morton Mine upper level	1988-1996	upper level, 1	86.0	88.0
		upper level, 2	88.0	90.0
		upper level, 3	90.0	92.0
		upper level, 4	92.0	94.0

In addition to mine excavation, an internal pressure boundary condition is applied to the SPR facility to simulate oil storage from 1980 to 1996. The pressure boundary condition simulating oil storage assumes that the mine is filled to the top of the upper level. After 1996, several options are investigated, including: (1) not removing the oil, (2) brine filling the SPR facility after oil removal, (3) brine filling both the SPR facility and the Markel Mine after oil removal, and (4) leaving the SPR facility empty after oil removal. Although leaving the oil in place is not an option under consideration (as DOE is removing oil from the facility at present), it was performed to investigate the relative effects of the other decommissioning options with respect to the present condition of the mine. The pressure boundary conditions applied to simulate brine fill assume that the brine level extends up to the top of the aquifer. All of the simulations terminate at the simulated year 2016, twenty years after decommissioning.

Constitutive Model and Failure Criteria for Rock Salt

The salt was modeled with an elastic/secondary creep constitutive model. The elastic constants are $E = 31.0$ GPa and $\nu = 0.250$. The creep strain rate depends on the equivalent deviatoric stress as follows:

$$\dot{\epsilon}^{cr} = A \tilde{\sigma}^n \exp\left(-\frac{Q}{RT}\right) \quad (2)$$

where

$\dot{\epsilon}^{cr}$ is the creep strain rate,

$\tilde{\sigma}$ is the effective or von Mises stress,

T is absolute temperature,

A (2.56×10^{-36} Pa^{-4.73}/sec) and n (4.73) are constants determined from fitting the model to creep data,

Q is the effective activation energy (12.0 kcal/mole),

R is the universal gas constant (1.987 cal/mole-K).

The structural stability of rock salt is evaluated in the present study based on two failure criteria: dilatant damage and tensile failure. The dilatant damage criterion, developed from laboratory data on Weeks Island salt (Ehgartner 1994), is used to delineate potential zones of dilatancy in the salt formation surrounding the storage facility. Dilatancy is attributed to microfracturing or changes in the pore structure of the salt, resulting in an increase in permeability and, hence, a flow path for groundwater. The dilatancy surface (Van Sambeek *et al*, 1993) is defined by a “damage” factor, D , which portrays the potential for dilatant behavior. The damage factor is expressed as $D = \sqrt{J_2}/(0.25 I_1)$, where J_2 is the second invariant of the deviatoric stress tensor, and I_1 is the first invariant of the stress tensor. When D is equal to or greater than one, the shear stresses in the salt are large compared to the mean stress and dilatant behavior is expected. The region of salt which experiences a change in its pore structure due to the excavation of underground openings has become known as the disturbed rock zone (DRZ).

The measured tensile strength of Weeks Island salt, based on laboratory samples, is approximately 1.07 MPa. Tensile cracking in rock salt tends to initiate perpendicular to the largest tensile stress in the rock sample. The largest tensile stress is one of the *principal stresses*. Because the maximum principal stress is the algebraically largest of the three principal stresses (in 3D space) and the largest normal stress in any direction, the potential for tensile failure exists if the maximum principal stress is tensile or numerically positive.

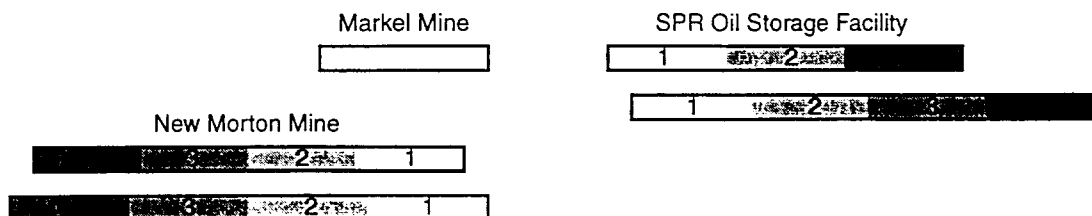


Figure 3: Illustration of mine subdivision for the purpose of simulating excavation.

Predicted Subsidence Rates Compared to Field Measurements

The planar 3D model was validated by comparing the predicted subsidence rates to those measured over the SPR and Morton facilities. The subsidence data, shown in Figure 4, indicate that the subsidence rates are nearly identical over the SPR and Morton facilities. The initial calculations (labeled *100 percent SPR pillar*) predicted that the subsidence rates over the SPR facility are much smaller than those over the Morton Mine. This discrepancy can be attributed to extensive spalling of the SPR pillars. The model assumes the mine pillars are in their original condition of 30.5 m (100 ft) square. However, pillar spalling up to 4.5 m (15 ft) thick was observed in the mine during a 1980 inspection (Acres, 1989). If 4.5 m (15 ft) of salt were spalled from all sides of the pillars, the resulting pillars would have a cross-sectional area equal to 49 percent of the original area. Two additional simulations were performed with pillar areas reduced to 70 and 50 percent of the original area. The results of these simulations are also shown in Figure 4. The predicted subsidence rates are very sensitive to the assumed pillar dimensions. The best qualitative match (approximately equal subsidence rates over both facilities) with the subsidence data was obtained with the 50 percent model. The shape and extent of the predicted subsidence rate contour matches the measured data. Like the data, this model predicts distinct subsidence troughs forming over the Morton and SPR facilities. The barrier of salt between the facilities is resisting the subsidence occurring on both sides of it. Like the data, the predicted subsidence trough over the New Morton Mine skews toward the right. The model overpredicts the subsidence rates over both facilities. This can be attributed to the semi-infinite characteristic of this model which will tend to overpredict mine closure and subsidence. Because the 50 percent model provides the best qualitative agreement with field data, this model was used for the remainder of the results presented in this paper. It should be noted that the Markel and New Morton mines are much younger than the SPR mine and have not exhibited the degree of pillar spalling observed in the SPR facility prior to oil fill.

Figure 5 shows a plot of predicted subsidence rate as a function of distance along the top of the dome for the four options investigated in this study. The subsidence rate predictions correspond to a simulated date of 1999. In all four options, the subsidence rate is nearly constant from 1997 to 2016. Brine filling the SPR facility results in a 97 percent reduction in the subsidence rates over the center of the SPR facility. Brine filling the Markel mine has a relatively insignificant effect on the differential ground subsidence over the facilities. The minimal impact of brine filling the Markel is due to the relatively small size and shallow depth of this facility relative to the underlying Morton Mine. Finally, leaving the SPR mine empty after oil removal

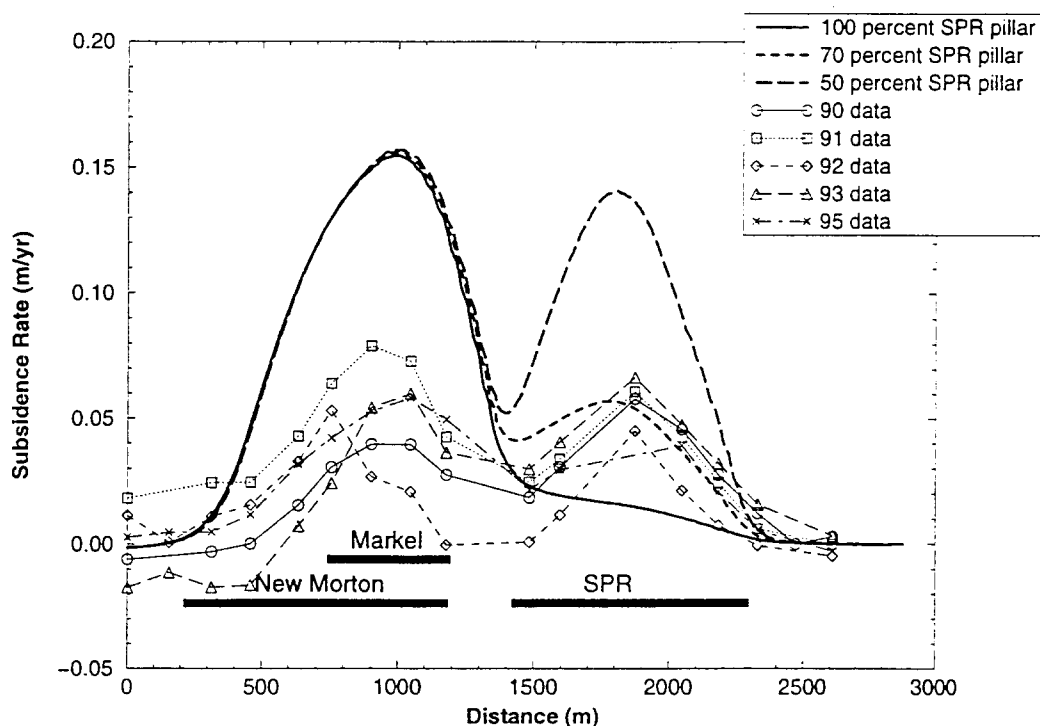


Figure 4: Predicted subsidence rates over the Weeks Island dome compared to field measurements.

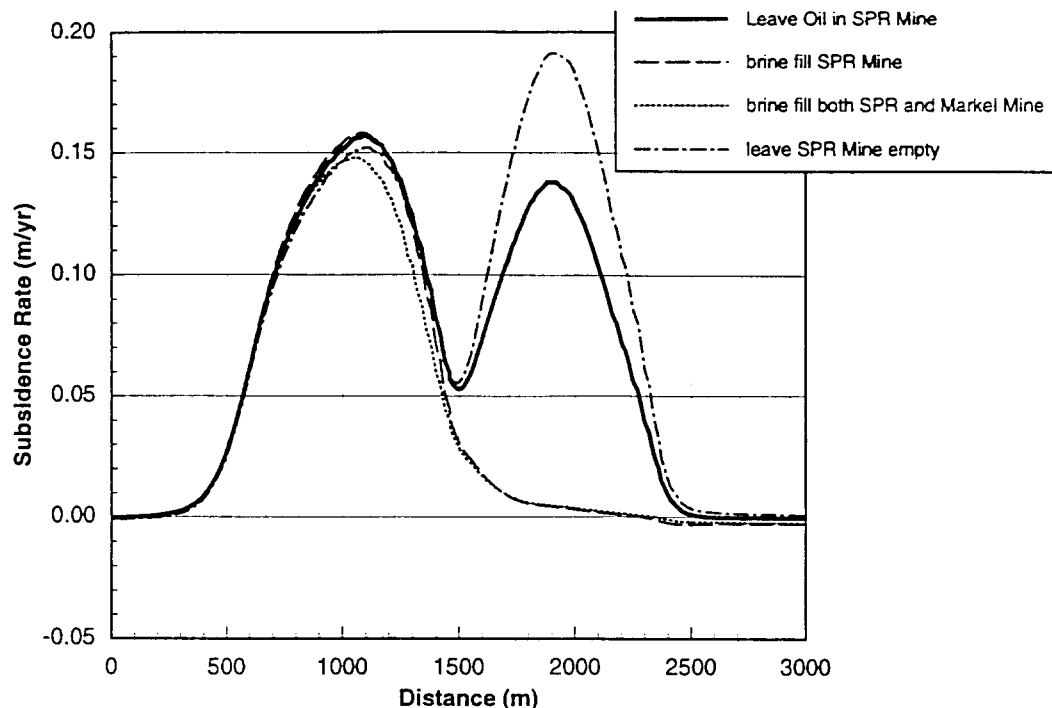


Figure 5: Predicted subsidence rate as a function of distance along the top of the dome for the four decommissioning options investigated in this study.

is predicted to result in a 40 percent increase in the subsidence rate over the SPR mine, while the predicted subsidence over the Morton Mine is predicted to remain nearly the same.

Tensile Failure Criterion

Figure 6 is a plot of the predicted maximum principal stress distribution in the Weeks Island salt dome in 1955 (completion of SPR upper level), 1976 (completion of SPR lower level), 1980 (completion of Markel), and 1996. Relatively large tensile stresses are predicted to develop with the mining of the SPR facility. The maximum value, indicated by a (*), occurs at the surface of the dome between the SPR and Morton facilities. This occurs because the salt overlying the mine boundaries is placed in bending as the mine pillars shorten (due to creep), and the salt directly over the mine subsides. The magnitudes of these predicted stresses are relatively large compared to the strength of Weeks Island salt (approximately 1 MPa). Consequently, a tensile fracture is likely to initiate at the surface of the dome and extend downward toward the mine. The predicted tensile region bridges the salt between the SPR mine and the surface of the salt dome. Based on these results, hydraulic connectivity due to tensile fracturing is likely to occur between the SPR facility and the overlying aquifer. There is very little change in the tensile stress distribution between the simulated dates of 1976 and 1980, indicating that the excavation of the Markel Mine has a negligible impact on the stress distribution in the dome. The excavation of the New Morton Mine has a much greater impact on the stress distribution, causing a tensile region to connect the Markel Mine to the top of the salt dome where the aquifer begins. These tensile regions are not predicted to bridge the salt between Morton Mine and the surface of the salt dome, indicating that the upper and lower levels of the New Morton Mine are not hydraulically connected to the overlying aquifer. This is due to the greater depth of the New Morton Mine relative to its width. These results also indicate that the SPR storage facility is not hydraulically connected to either of the neighboring excavations, making it safe for brine fill.

The long term effects of the two primary decommissioning processes, brine fill and leaving the facility empty, on the stress distribution around the excavations are shown in Figure 7. Brine, having a greater density than the oil, effectively reduces the tensile stresses due to the SPR excavation with no apparent adverse structural effects on the neighboring facilities. Compared to oil filled conditions, leaving the SPR facility empty results in no significant changes in the stress distribution surrounding the facility.

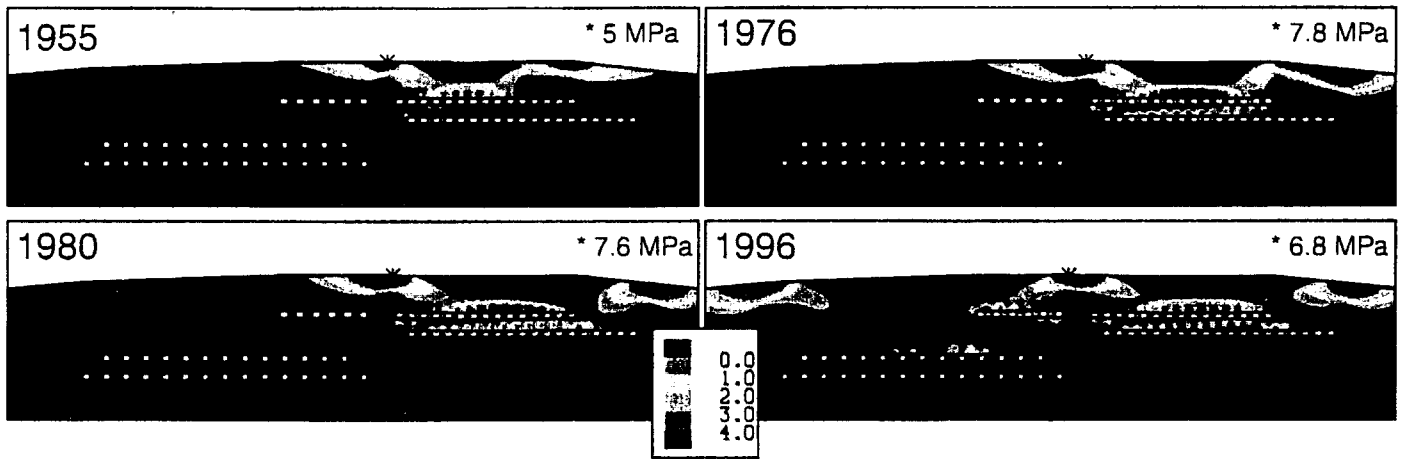


Figure 6: Maximum principal stress distribution (MPa) in the Weeks Island dome at times corresponding to completion of the SPR upper level (1955), completion of SPR lower level (1976), completion of Markel (1980), and prior to decommissioning (1996).

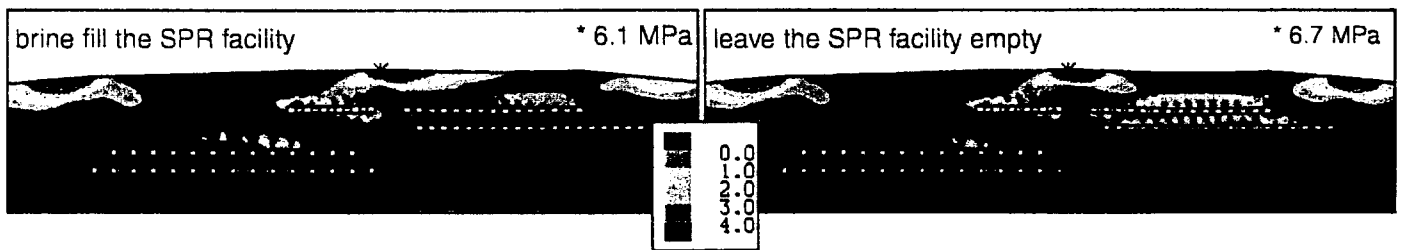


Figure 7: Maximum principal stress distribution (MPa) in the Weeks Island dome 20 years after decommissioning by (a) brine filling the SPR facility, and (b) leaving the SPR facility empty.

Dilatant Damage Criterion

Figure 8 is a plot of the calculated dilatant damage potential in the Weeks Island dome in 1955 (completion of SPR upper level), 1976 (completion of SPR lower level), 1980 (completion of Markel), and 1996. A relatively large disturbed rock zone (DRZ) is predicted to develop (where $D < 1$) with the mining of the upper level of the SPR facility. The DRZ is caused by the bending stresses over the boundaries of the mine, increasing the deviatoric stress relative to the hydrostatic component. At the completion of the upper level, the DRZ is predicted to couple the SPR facility to the top of the salt dome and the overlying aquifer. The DRZ grows in both size and magnitude with the excavation of the lower level of the SPR mine, coupling the two levels together. Although the Markel Mine is at the same depth at the upper level of the SPR mine, the excavation of the Markel Mine has a relatively small impact on the dilatant damage distribution. At the completion of the Markel excavation (1980), the Markel is not predicted to be coupled with the overlying aquifer. This is due to the small horizontal extent of the mine relative to its depth. Like the SPR facility, the excavation of the New Morton Mine causes a DRZ to develop at the surface of the dome, extending toward the mine. The DRZ is not predicted to couple the upper and lower levels of the New Morton Mine with the overlying aquifer. Again, this is due to the greater depth to width ratio of the mine. However, the DRZ resulting from the excavation of the New Morton Mine does intersect the Markel Mine.

The long term effects of the two primary decommissioning processes, brine fill and leaving the facility empty, on the dilatant damage potential are shown in Figure 9. Brine filling reduces the dilatant damage potential in the region local to the SPR facility, creating a stress state more conducive to salt healing. Compared to oil filled conditions, leaving the SPR facility empty results in no significant changes in the DRZ surrounding the facility.

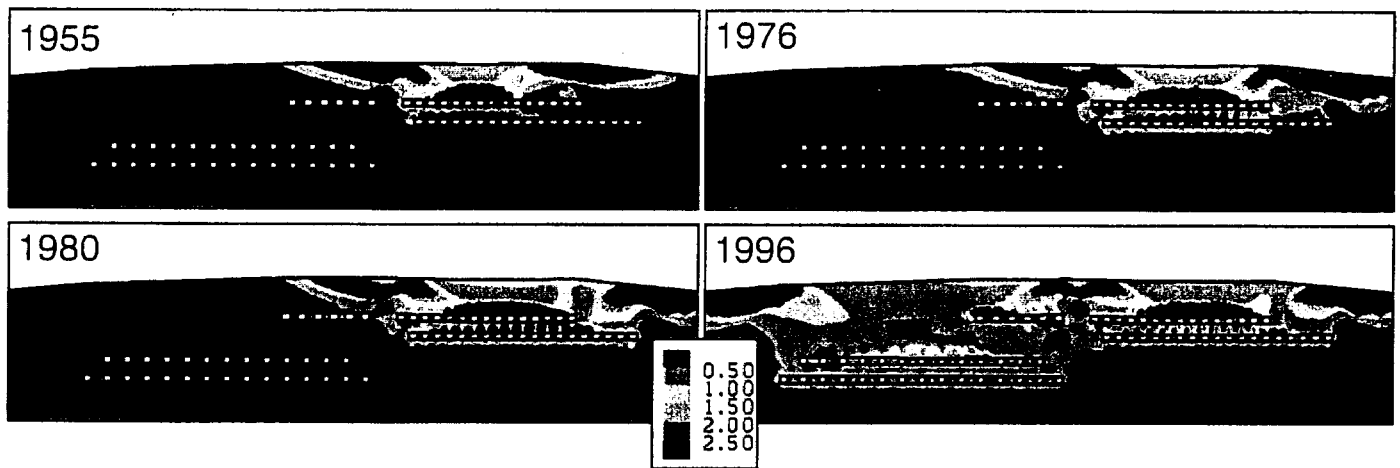


Figure 8: Dilatant damage potential distribution in the Weeks Island dome at times corresponding to completion of the SPR upper level (1955), completion of SPR lower level (1976), completion of Markel (1980), and prior to decommissioning (1996).

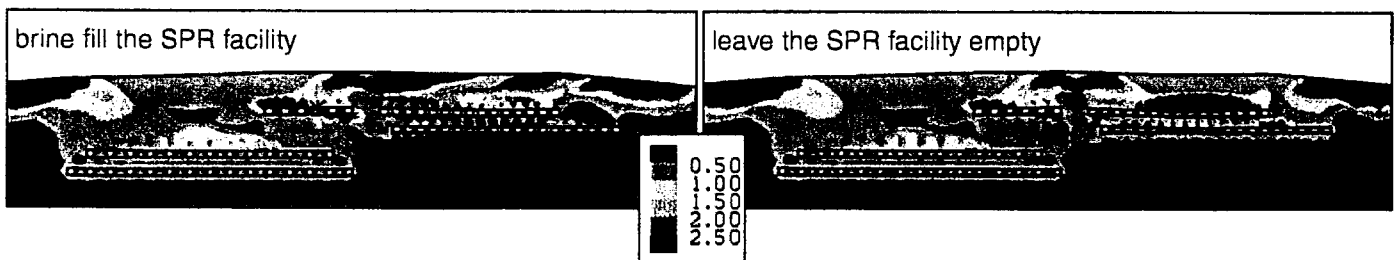


Figure 9: Dilatant damage potential distribution in the Weeks Island dome 20 years after decommissioning by (a) brine filling the SPR facility, and (b) leaving the SPR facility empty.

Undermining Calculations

The DOE is interested in the structural response of mining activities beneath the decommissioned SPR facility, should Morton decide to extend their mine in the future. Hydrological coupling between the undermining operations and the brine filled SPR facility could make for unsafe mining conditions. Undermining simulations were performed in which the 366 m (1200 ft) level of the New Morton Mine is extended beneath the SPR mine. It was assumed that the additional level would take ten years to excavate, beginning at a simulation time corresponding to 1997. The results of these simulations are presented in Figure 10 in terms of the tensile stress and dilatant damage failure criteria at a simulation time corresponding to the year 2010. The simulations provide no indication that the decommissioned facility will become hydrologically coupled to the Morton mine. More importantly, the simulations indicate that the undermining operations could improve the stress distribution over the SPR facility by moving the DRZ and the tensile region from over the SPR facility boundary. These results suggest that when mining lower levels, a mine's service life can be increased by mining beyond the extent of the upper levels.

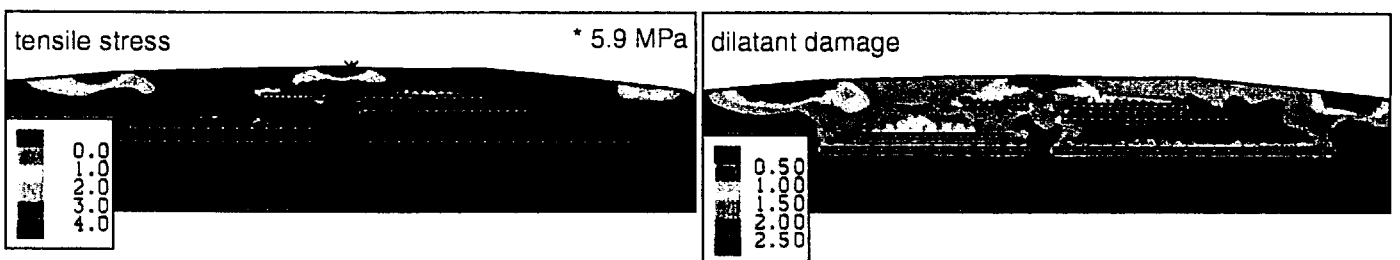


Figure 10: Dilatant damage potential distribution and maximum principal stress distribution in the Weeks Island dome after mining beneath the SPR facility is completed (2010).

By including all three mines, sequential excavation, and pillar deterioration of the SPR facility, these calculations are the most comprehensive simulations performed of the Weeks Island salt dome to date. The simulations show no indication that the Weeks Island SPR facility is hydrologically coupled to either the New Morton or Markel mines. Hence, brine filling the decommissioned facility should pose no serious threat to Morton's production activities. In spite of the close proximity of the three facilities, the effects of decommissioning the Weeks Island SPR facility are very localized to the mine and the surface directly above the mine. Brine filling of the Weeks Island SPR facility is predicted to reduce surface subsidence rates by 97 percent and reduce the dilatant damage potential local to the SPR mine. This should reduce the rate of further deterioration of the excavation. Although these simulations were performed in the specific interest of the SPR, the results should be of general interest to mine designers. First, the simulations show a strong dependency of subsidence rate on the condition of the mine pillars. Furthermore, the results of this simulation indicate that there is a critical mine depth to width ratio above which the mine will become hydraulically connected with the overlying aquifer. The undermining simulations show that this hydraulic connectivity can be controlled by increasing the lateral extent of additional mine levels. However, other conventional room and pillar mines may face similar eventualities. Structural simulation tools can and should be used in mine design and planning to prevent this type of problem.

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